FINAL TECHNICAL REPORT

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"Ground-based and Voyager occultation studies of Neptune's rings"

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Scientific goals

The principal goals of this research were as follows:

1. To carry out a thorough analysis of Earth-based stellar occultation data on the Neptuinen ring system, in the light of the Voyager observations in August 1989;
2. To combine the results of Voyager and Earth-based studies to determine the orbital (and photometric) properties of the ring arcs.

Under item (1) was included a comprehensive search for additional observations of the arcs embedded in the Adams Ring, as well as the goal of setting stringent upper limits on the equivalent widths (i.e., radially integrated optical depths) of the continuous rings.

Summary of work accomplished

The major job of re-analyzing all our ground-based occultation observations between 1984 and 1988 — a total of eight data sets — was completed in 1993, and the results submitted for publication in November of that year. Due largely to delays in the reviewing process, the paper has only recently been published (Nicholson, Mosqueira and Matthews [1995]). This paper provides a complete documentation of our Neptune occultation observations (with the exception of a single event in July 1992, which is currently being written up in collaboration with Dr. R. French), and is intended to serve as a reference for future workers.

In this paper, we describe one additional (but unconfirmed) observation of a ring arc from 9 July 1988, as well as what we believe to be the first ground-based detection of the LeVerrier Ring, at an equivalent width of 520 ± 55 m. This is comparable to that observed by the Voyager PPS experiment. A complete set of equivalent width profiles is included, from which is derived an upper limit of 75 m on the equivelent width of the Adams Ring well away from the arc region. A combined statistical analysis with other published occultation data (Sicardy et al. [1991] *Icarus*, **89**, 220) indicates that (i) the particles in the Adams Ring may be more reflective than the particles in the arcs; and (ii) that the LeVerrier Ring may be azimuthally variable or even clumpy.

Our second goal has, as yet, been only incompletely realized. A dynamical model of the Adams Ring based on the Voyager imaging and occultation observations was developed by Porco (1991) (*Science*, **253**, 995), involving resonant control of the arcs by the nearby satellite Galatea. We have tested the earth-based arc observatioons against this model, and find that all are consistent with it, except for the putative July 1988 event. Uncertainties

in the absolute radii of the ground-based arc detections of 25–50 km appear to preclude further refinement of the Porco model with these data, although we were able to confirm that the Adams Ring does indeed define Neptune's equatorial plane with even greater precision than do Voyager navigation data (Jacobson et al. [1991] *Astron. & Astrophys.* **247**, 565). These results were also presented in Nicholson et al. (1995).

A comprehensive discussion of all available data (Voyager and ground-based) on the Neptunian rings and arcs, together with models for the current dynamical state and possible evolutionary history, was completed in 1993/1994 for the University of Arizona book "Neptune and Triton", to be published in 1995. As second co-author of this chapter, I was responsible for reviewing all of the occultation data, as well as for parts of the dynamics and particle properties discussions. These discussions rested heavily on the *Icarus* paper, but extended the photometric discussion of the ring particles with the use of as yet unpublished imaging analyses by M. Showalter and J. Cuzzi.

Finally, I note that graduate student Ignacio Mosqueira, who was supported for 2 years under this grant and who carried out much of the occultation data analysis, has subsequently presented and defended his Ph.D. thesis and is now an NRC Post-Doctoral Fellow at NASA Ames Research Center, CA.

Publications under this Grant

Nicholson, P.D., I. Mosqueira and K. Matthews (1995). "Stellar occultation observations of Neptune's rings: 1984–1988." *Icarus*, **113**, 295-330.

Porco, C.C., P.D. Nicholson, J.N. Cuzzi, J.J. Lissauer and L.W. Esposito (1995). "Neptune's ring system." In *Neptune and Triton*, D. Cruikshank, Ed., Univ. of Arizona Press, Tucson.

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Stellar Occultation Observations of Neptune's Rings: 1984–1988

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Data from eight stellar occultations by Neptune between 1984 and 1988 are analyzed to set limits on the optical depths of the continuous Adams and Le Verrier Rings, and to search for previously unidentified occultations by the arcs in the Adams Ring. We employ the approach introduced by Sicardy *et al.* (1991), *Icarus* 89, 220–243) and convert the raw lightcurves to radial profiles of equivalent width $E(r)$, the fraction of incident starlight removed by ring material at normal incidence integrated over a specified radial range, or "window." In order to optimize the search for narrow rings, the window length is fixed at 15 km. Radii in Neptune's equatorial plane are calculated using the Neptune pole direction determined by Jacobson *et al.* (1990), *AIAA/AAS Astrodynamics Conference*, pp. 157–167). Using data from the occultation of 20 August 1985, we set a 3σ upper limit of 75 m on the equivalent width of the Adams Ring at a longitude 120° away from the arc region, near the location of minimum ring brightness in the *Voyager* images (Showalter and Cuzzi 1994, in preparation). This limit is for a maximum ring width of 15 km; for a maximum ring width of 50 km, the corresponding upper limit is $E \leq 210$ m. Combining the results from this data set with similar upper limits obtained by Sicardy *et al.* (1991) with a 50-km window size, and assuming that the Adams Ring is azimuthally homogeneous away from the arc region, we find that the equivalent width of this ring is ≤90 m at the 90% confidence level, or ≤ 5% of the measured equivalent width of the Egalité arc. A comparison of this result with the relative brightnesses of ring and arcs observed at low phase angles in *Voyager* images (Showalter and Cuzzi 1994) suggests either that the particles in the Adams Ring have higher albedos than those confined within the arcs, or that the width of the continuous ring significantly exceeds 50 km. The 20 August 1985 lightcurve has also yielded the first tentative earth-based detection of the Le Verrier Ring, with an overall radial width of 135 km and an equivalent width of 520 ± 55 m at $\lambda 2.2$ μm which are similar to results obtained by the *Voyager* Photopolarimeter occultation experiment at $\lambda 0.27$ μm (Horn *et al.* 1991, *Geophys. Res. Lett.* 17, 1745–1748). The ratio $E_{PPS}/E_{2.2\mu m} = 1.3 \pm 0.3$. The mean radii of both occultation profiles—53055 and 53125 km, respectively, projected into the ring plane determined by Porco *et al.* (*Neptune and Triton Conference, Tucson, AZ, 1992*) and Showalter and Cuzzi (1992), *Bull. Am. Astron. Soc.* 24, 1029)—are significantly less than the image-derived radius of 53200 ± 20 km (Porco *et al.* 1992). It is conceivable that this discrepancy could be due to an unrecognized inclination and/or eccentricity. A comparison of our putative detection of the Le Verrier Ring with upper limits set by Sicardy *et al.* (1991) suggests that this ring must be azimuthally inhomogeneous on scales of ~10°, if our detection is real. A feature in the vicinity of the Adams Ring at the predicted longitude of the Liberté arc was seen in data obtained on 9 July 1988, but a discrepancy of 270 km between the calculated radius and the known semi-major axis of the ring seems to rule out an identification with the arc. Attempts to fit a precessing ellipse model to all available occultation data for the Adams Ring which will also accommodate this observation are in vain. The remaining occultation-derived radii for this ring are found to be consistent with the resonant-perturbation model of Porco (1991, *Science* 253, 995–1001), and suggest strongly that the Adams Ring lies in, or very close to, Neptune's equatorial plane.

I. INTRODUCTION

Prior to the encounter of the Voyager spacecraft with Neptune in August 1989 (Stone and Miner 1989), approximately 25 stellar occultations were observed from Earth-based telescopes (Freeman and Lyngå 1970; Elliot *et al.* 1981, 1985; Reitsema *et al.* 1982; Hubbard *et al.* 1985, 1986; French *et al.* 1985; Covault *et al.* 1986; Nicholson *et al.* 1990; Sicardy *et al.* 1991). After the discovery of the "ring arcs" on 22 July 1984 (Hubbard *et al.* 1986) a primary goal of these observations was the characterization of the rather puzzling Neptunian ring system. Two further observations of incomplete rings, or arcs, were reported by Covault *et al.* (1986) (from 7 June 1985), and by Nicholson *et al.* (1990) and Sicardy *et al.* (1991) (from 20 August 1985). The radial widths of the arcs were observed to be 8–15 km, while the normal optical depths

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NEPTUNE'S RING SYSTEM

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We review the current state of knowledge regarding the structure, particle properties, kinematics, dynamics, origin, and evolution of the Neptune rings derived from Earth-based and Voyager data. Neptune has a diverse system of five continuous rings—2 broad (Galle and Lassell) and 3 narrow (Adams, Le Verrier, and Arago)—plus a narrow discontinuous ring sharing the orbit of one of its ring-region satellites, Galatea. The outermost Adams ring contains the only arcs observed so far in Voyager images. These were responsible for most of the Earth-based stellar occultation detections of circum-Neptunian material in the mid-1980s. Three other Earth-based detections recorded material of some sort within Lassell and Galle, and interior to Galle. The five arcs vary in angular extent from ~1° to ~10°, and exhibit internal azimuthal structure with typical spatial scales of ~0.5°. All five lie within ~40° of longitude. Combined analysis of Earth-based occultation data and Voyager photometry yields typical optical depths of $\tau_{arcs} \sim 0.1$, and $\tau \sim 0.003$ for the two narrow rings Adams and Le Verrier. Dust is present throughout the Neptune system and measureable quantities of it were detected over Neptune's north pole. The Adams ring (including the arcs) and the Le Verrier ring contain a significant fraction of dust, comparable to that observed in Saturn's F ring; Lassell appears to have a different mix of particle sizes than Le Verrier or Adams. The Neptune ring particles are as dark as those in the rings of Uranus (with a single-scattering albedo $\tilde{\omega} \sim 0.04$), are probably red, and may consist of ice "dirtied" with silicates and/or some carbon-bearing material. A kinematic model for the arcs derived from Voyager data, the arcs' physical characteristics, and their orbital geometry and phasing are all roughly in accord with single-satellite arc shepherding by Galatea, though the presence of small kilometer-sized bodies embedded either within the arcs or placed at their Lagrange points may explain some inconsistencies with